Pomeron and the Reggeized Glueball/Sigma

Leonard S. Kisslinger
Department of Physics,
Carnegie Mellon University, Pittsburgh, PA 15213
and
Wei-hsing Ma
Institute of High Energy Physics, Academia Sinica
Beijing 100039, P. R. China

February 1, 2008

Abstract

It has long been believed that the Pomeron, which has been successful in phenomenological fits to high energy scattering data, is associated with gluonic exchange. By determining the Regge-nucleon vertex in terms of previously determined glueball-quark coupling we show that the Pomeron might be related to the Regge trajectory defined by a light scalar glueball/sigma system and a tensor glueball, which involves complicated nonperturbative QCD. We predict a tensor glueball at 2.8 GeV.

PACS Indices: 12.40.Gg, 12.38.Lg, 13.85.Dz, 13.60.Le

1 Introduction

The Regge picture[1] is successful for accounting for high energy elastic hadronic scattering and diffractive processes, however, Regge trajectories of established hadrons are not consistent with high energy data[2]. Early in the attempts to fit experiment with phenomenological Regge models it was suggested that an additional Regge trajectory that could correspond to a particle with vacuum quantum numbers at it lowest energy was needed. In order to fit the behavior of high energy ($\sqrt{s}$) elastic or diffractive cross sections the pole position in the J-plane, $\alpha(s)$, of the Regge pole that dominates high energy scattering should have the property that $\alpha_{\mathrm{vac}}(0) \simeq 1.0$[3]. This is the Pomeron.

There has been a problem in understanding Regge phenomenology and high energy elastic and diffractive scattering, since none of the Regge trajectories for t-channel exchange associated with known mesons can fit into the Pomeron trajectory with $\alpha(0) \simeq 1.0$. There have been many conjectures about the nature of the Pomeron, but the dynamics leading to the Pomeron is still not understood. As was observed by a number of workers in this field[2] it seems that there is no simple resonance or pole on the Pomeron trajectory.

A phenomenological Pomeron exchange model with a vector-type Pomeron-nucleon vertex was proposed[4]

$$V^{P-N} \quad = \quad \beta\gamma^{\mu}\mathrm{F}_1(\mathrm{t}), \tag{1}$$

where $\mathrm{F}_1(\mathrm{t})$ is the isoscalar nucleon form factor and β is a parameter, and has been used in a number of fits to high energy experimental data. We refer to this as the DL model. Good fits to pp and p$\bar{\mathrm{p}}$ elastic scattering, diffractive dissociation[5] and ρ-meson electroproduction[6] have been obtained with a value of the vertex parameter $\beta \simeq 6.0$ Gev^{-1}. The trajectory found in this model has an intercept $\alpha(0) = 1.08$ and a slope $\alpha'(0) = 0.25$ GeV^{-2}. It is the objective of the present work to attempt to derive this vertex parameter with nonperturbative QCD by assuming that the Pomeron is associated with a glueball/sigma type trajectory and using known properties of glueballs and a conjecture of a light scalar glueball/sigma system, discussed below.

In terms of Quantum Chromodynamics (QCD) a hadron that is not a $\bar{q}q$ meson and has vacuum quantum numbers is a candidate scalar glueball, and many theorists have stated that it is expected that the Pomeron is related in some way to glueball exchange. There are two distinct theoretical efforts related to Regge theory and the Pomeron: the so-calleed soft and hard Pomerons. The "soft" Pomeron is essentially the original Pomeron, which would give universal fits to elastic and diffractive processes at high energies. The program of "hard" Pomeron physics is a study of high energy, high momentum transfer process. See, e.g., Ref[7] for a description of the main features of these two programs. In the present article we use the terminology Pomeron for the soft Pomeron.

The theoretical "hard" Pomeron studies are an extension of the first detailed theoretical model for Regge exchange, called the multiperipheral model[8]. Attempts to describe the Pomeron by gluonic exchange processes started with a bag model picture[9] and by an explicit model of two-gluon exchange[10]. Phenomenological fits using two-gluon exchange

have been carried out[11]. Attempts to put this model on sounder theoretical ground using perturbative QCD have led to an integral equation[12] for the two-gluon ladder exchange. See Ref.[13] for a review of attempts to derive the Pomeron from gluonic ladders. There has also been a suggestion[14], based in part on the early two-gluon exchange picture[10], that experimentally observed rapidity gaps are evidence for a gluonic exchange picture of the Pomeron.

However, for the soft Pomeron (the Pomeron) it is expected that nonperturbative QCD is required for a microscopic treatment. Although the Pomeron trajectory is higher than all meson trajectories, it is possible that a scalar glueball could be on the daughter trajectory of the Pomeron, which is the conjecture of the present article. There have been many theoretical treatments of glueballs using QCD sum rule methods[15, 16]. Recently, it was shown that mixed scalar glueballs and mesons have masses in the 1300-1500 MeV region, which cannot be on the trajectory of the Pomeron, however, there is also sum rule solution at energy far below the region for scalar mesons[17]. More recently it has been conjectured that the low-energy scalar glueball is strongly coupled to the sigma/$\pi\pi$ system which results in a broad, low-energy scalar resonance[18]. It is this coupled-channel resonance, which we call the Glueball/Sigma that we consider here. With the assumption that the Pomeron is associated with a glueball/sigma-Regge trajectory, a nonperturbative treatment of the Pomeron-Nucleon vertex, $\mathrm{V^{P-N}}$, can be carried out using the glueball solutions obtained by QCD sum rules.

In the present note we explore the possibility that the low-lying glueball/sigma might be related to the Pomeron trajectory in the sense of a daughter trajectory[19] by finding the glueball-nucleon coupling for the diffractive region and comparing it to the phenomenological Pomeron-nucleon vertex. The nature of the trajectory is not understood, and the dynamics of the Glueball/Sigma is modelled by fits to experiment and not understood dynamically. We review the QCD sum rule work on mixed scalar mesons and glueballs and the idea of the sigma/glueball in Sec. 2; and calculate the scalar glueball/sigma coupling to the nucleon in the next two sections, showing that the coupling is consistent with the phenomenological pomeron-nucleon coupling. We give our conclusions in Sec. 5.

2   Glueballs, the Glueball/Sigma and the Pomeron

Since the Pomeron is almost certainly mainly composed of glue, it is natural to consider the relationship between glueballs and the Pomeron. In the present work we are dealing with the scalar 0^{++} states. If such a glueball is on a Regge trajectory associated with the Pomeron, it would lie on the daughter, as we discuss below. In this section we shall briefly review recent theoretical work on scalar glueballs in order the clarify the nature of the hypothesized Glueball/Sigma. In the energy regions where scalar mesons and scalar glueballs are both present it is expected that they should mix[15]. In the QCD sum rule method this leads one to consider a mixed meson and glueball current,

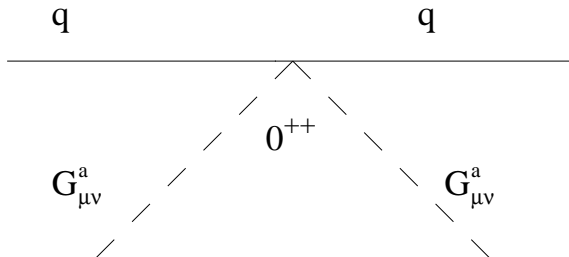$$\eta(x) \;\; = \;\; c_1 G \cdot G + c_2 \bar{q}(x) q(x). \tag{2}$$

3

Fig. 1 Quark propagating in an external glueball field

The constants c_1, c_2, which are determined by the sum rules, give the composition of the lowest state as being mainly glueball or mainly meson. Using this form[17] it was shown that the purely mesonic solution at about 1 GeV, which would be associated with the $f_o(980)$ does not occur, but mixed meson/glueball solutions are found that can be interpreted to be the $f_o(1370)$, which turns out to be mainly meson, and the $f_o(1500)$, which is mainly glueball. Most striking is the result that far below the region of scalar mesons there is a pure glueball solution in the region 300-600 MeV. The conjecture that this glueball might be very strongly coupled to the low energy 0^{++} two-pion system[18] follows from the experimental analysis of possible glueballs by the BES group[20], which showed that glueballs have a large branching ratio to the sigma, a resonance seen in the low-energy scalar, isoscalar $\pi - \pi$ system[21]. We call this coupled-channel phenomenon the Glueball/Sigma, and investigate its possible relationship to the pomeron. Of course, since the Pomeron intercept is about 1, the Glueball/Sigma cannot be on the pomeron trajectory, but could be on the daughter[19] to the pomeron. The $f_o(1500)$ and $f_o(1700)$ candidate glueballs[22] might be on some gluonic Regge trajectories, but not on the Pomeron or its daughter trajectories.

A most important aspect of theory is that if the glueball/sigma conjecture is correct, that is if the low-energy glueball is a pole that drives the sigma two-pion resonance with a mass and width of about 400 MeV, then from the experimental Breit-Wigner resonance the gluon-sigma coupling matrix element is determined. As we shall now show, from this one can predict the glueball-nucleon coupling and compare it to the phenomenological Pomeron-nucleon coupling. We do this in the next two sections.

3   Scalar Glueball-Nucleon Coupling

First let us look at a very simple for glueball-nucleon coupling by finding the coupling of a glueball to a quark. Let us assume that the quark is moving in an external glueball field, as depicted in Fig. 1. This effective quark propagator is given in space-time by the expression

$$S_q(x)^{GB} \quad = \quad \int d^4y < T[\bar{q}(x)q(y)J^{GB}(y)\bar{q}(y)q(0)] >, \tag{3}$$

4

where J^{GB}, the scalar glueball current, is defined with the normalization $J_{GB} = 3 \; gG \cdot G/(4\pi)^2$. Making use of the fact that the effective quark propagator defined in Eq.(3) will be used in the region $x \to y \to 0$, the integral in Eq.(3) can be approximated by the low energy theorem [15]

$$\int d^4y < T[q(0)\bar{q}(0)J^{GB}(y)] > \; \simeq \; \frac{32}{9} < 0| : \bar{q}(0)q(0) : |0 > . \tag{4}$$

Using the approximation of Eq.(4) in Eq.(3) we obtain for the effective guark propagator at momentum $k \to 0$

$$S_q(k \to 0)^{GB} \; \simeq \; \frac{32a}{9(2\pi)^2 m_q \lambda} \; , \tag{5}$$

with a $= \; < \bar{q}q > (2\pi)^2 \simeq 0.55 \; \text{GeV}^3$. The quantity $\lambda =< 0|J_{GB}|GB >$ is a normalization factor given in Refs.[15, 17] Using a quark mass of 8 MeV and a glueball mass of 600 MeV this gives for the glueball-nucleon vertex

$$V^{GB-N}(t \to 0) \; \simeq \; 8.0 GeV^{-1}. \tag{6}$$

Comparing to Eq.(1) the coupling strength is of the order of magnitude, but is a scalar rather than a vector coupling as in the DL model.

We emphasize that the glueball solution found by using the current J^{GB} is not the $f_0(1500)$. The $f_0(1500)$ has properties[22] suggesting that it is a mixed glueball/meson, which is consistent with a sum rule solution with a mixed J^{GB} and $\bar{q}q$ current[17] in the 1500 MeV region. It has been understood for many years that the f_0 cannot lie on the Pomeron trajectory[2]. The glueball we assume is part of the coupled low-energy glueball/σ, which is observed as a pole at $400 + 400i$ in the $\pi - \pi$ scalar, isoscalar amplitude[18, 21].

4   High-Enegy Glueball-Nucleon Coupling

In this section we use the methods developed for deep inelastic scattering to derive the glueball-nucleon coupling for use in high-energy processes, and see if the result is consistent with the Pomeron coupling.

Recall that inclusive deep inelastic scattering (DIS) cross section can be obtained from forward Compton scattering (see e.g. Ref.[23]), $\gamma + p \to \gamma + p$ by using an operator product expansion in a light-cone representation. The hadronic tensor for a proton target is $W_{\mu\nu} = \text{Im}[T_{\mu\nu}]/(2\pi)$,

$$T_{\mu\nu} \; = \; i \int d^4x e^{ik \cdot x} < p|T[J_\mu(x)J_\nu(0)]|p >, \tag{7}$$

with the electromagnetic current $J_\mu(x) = \bar{q}(x)\gamma^\mu Q q(x)$, where Q is the charge operator. In analogy to DIS, we evaluate $T_{\mu\nu}$ using the diagram shown in Fig. 2. Introducing a light-cone
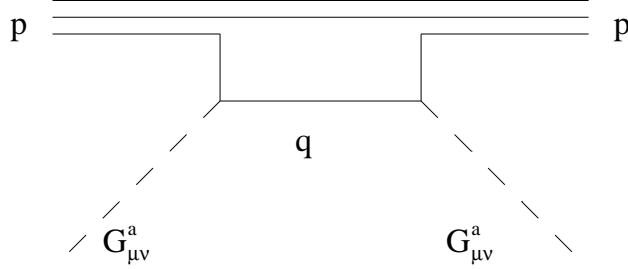
Fig. 2 Gluonic coupling for high energy elastic scattering

representation with momentum $(k^+, \vec{k}^\perp, k^-)$, one finds in the scaling region

$$W_{+,-} = i\frac{2}{\pi}\int dx^- e^{ik^+x^-} < p|T[q_-^\dagger(x_-)Q^2 q_-(0)]|p >, \qquad (8)$$

where q_- is a light-cone projection of the quark field. The expression in Eq.(8) gives the parton model for the structure functions, with $W_{+,-} = F_2(x)/2x$ expressed in parton distribution functons, with x the scaling variable.

Let us consider the forward gluon-proton scattering T-matrix

$$T = i\int d^4x d^4y e^{ik\cdot(x-y)} < p|T[J_c(x)J_c(y)]|p >, \qquad (9)$$

with the color current $J_c(x) = \bar{q}(x)\gamma^\mu A_\mu(x)q(x)$. This is the analog to the forward Compton T-matrix with the electromagnetic potential replaced by the gluonic color potential. We use the fixed point gauge, $x_\mu A^\mu(x) = 0$, and $A_\mu(x) = -G_{\mu\nu}(0) x^\nu/2$, with $G_{\mu\nu} = \sum_{a=1}^8 \tau^a G_{\mu\nu}^a$, τ^a being the SU(3) color operator. Keeping the lowest-dimension contractions one finds the standard form

$$T = \frac{i}{4}\frac{\partial}{\partial k^\alpha}\frac{\partial}{\partial k^\beta}i\int d^4x d^4y e^{ik\cdot(x-y)}Tr[S_q(-x)\gamma^\mu S_q(x)\gamma^\nu < g^2 G_{\mu\alpha}G_{\nu\beta} >] \qquad (10)$$

Proceding as in DIS, and making use $\partial S_q(k)/\partial k \to S_q/m_q$ in the limit $k \to 0$, one finds

$$T \simeq K\frac{\partial}{\partial k^+}\int dx e^{ikx}S_q(x) \qquad (11)$$

$$K = \frac{2a}{27m_q\lambda}.$$

Taking the value 8 MeV for the quark mass we find for the vertex parameter in $V^{GB-N}(t \to 0)$

$$\beta \simeq 6.6 GeV^{-1}, \qquad (12)$$

compared to the phenomenological DL value[5] of 6.0 GeV^{-1}. From this we conclude that the Pomeron trajectory could be closely related to the coupled scalar glueball/sigma system.

6

Of course the value of $\alpha(0) \simeq 1.0$. is not consistent with a simple interpretation of a light scalar glueball on the Pomeron trajectory, as has been known for decades[2]. However, one possible interpretation is that the Glueball/Sigma system is on the first "daughter" trajectory[19] of the Pomeron. Since daughter trajectories satisfy $\alpha(0)_{\text{daughter}} = \alpha(0) - 1.0$, and the daughter and Regge trajectories are parallel, this is a possible solution. In potential models[19] it is shown that the residue of the daughter results in a cancellation of an unwanted singulaity in the Regge picture. Daughters also appear in dual models[2].

A recent calculation[24] has shown that the $\xi(2230)$ observed at BES[20], which has some characteristics of a glueball, but is not yet established as a 2^{++} resonance, might be on the Pomeron trajectory. Using experimental pp cross sections the branching ratio to $p\bar{p}$ was predicted, which serves as a test of the nature of the $\xi(2230)$. From the phenomenological slope of the Pomeron/daughter trajectory[11], $\alpha'(0) = 0.25$ GeV^{-2}, we predict that a tensor glueball on the same daughter trajectory as the light glueball/sigma will be found at about 2.8 GeV, so that a tensor glueball associated with the scalar Glueball/Sigma is predicted to occur at an energy about 600 Mev higher than the $\xi(2230)$. As noted in Sec. 2, the $f_o(1500)$ and $f_o(1710)$ candidate scalar glueballs are not on the Pomeron or daughter trajectories.

5   Conclusions

We have shown that the low-energy glueball that recently has been proposed as a coupled glueball-sigma system couples to a nucleon with the strength roughly in agreement with phenomenological Regge Pomeron fits to a number of scattering and production experiments at high energy. In this picture we propose that a light scalar Glueball/Sigma lies on a daughter of the Pomeron Regge trajectory. This is consistent with the $\xi(2230)$ being a tensor meson/glueball on the Pomeron trajectory and a higher-mass tensor glueball, we predict to be at 2.8 GeV, being on the daughter trajectory with the scalar glueball. The glueball/sigma system is complicated and the dynamics of this system are certainly not understood by the authors, however, this could also be the nature of the Pomeron.

References

[1] T. Regge, Nuovo Cimento **14** (1959) 951.

[2] P.D.B. Collins, "Introducton to Regge Theory (Cambridge University Press, Cambridge, 1977), reviews Regge phenomenology and the Pomeron.

[3] G.F. Chew and S.C. Frautschi, Phys. Rev. Lett. **7** (1961) 394.

[4] P.V. Landshoff and J.C. Polkinghorne, Nucl. Phys. **B32** (1971) 541.

[5] A. Donnachie and P. V. Landshoff, Nucl. Phys **B231** (1984) 189; **B244** (1984) 322.

[6] A. Donnachie and P.V. Landshoff, Phys. Lett. **B185** (1987) 403; M.A. Pichowsky and T-S. H. Lee, Phys. Lett. **B379** (1996) 1.

[7] E. Levin, hep-ph/9808486,"An Introduction to Pomerons", Workshop on diffractive physics, Rio de Janeiro (1998).

[8] D. Amati, A. Stanhellini and S. Fubini, Nuovo Cimento **26** (1962) 896.

[9] F.E. Low, Phys. Rev. **D12** (1975) 163.

[10] S. Nussinov, Phys. Rev. Lett. **34** (1975) 1986.

[11] A Donnachie and P.V. Landshoff, Nucl. Phys. **B311** (1989) 509; J.M. Laget and R. Mendez-Galain, Nucl. Phys. Nulc. Phys. **A581** (1995) 397.

[12] E. Kuraev, L. Lipatov and V. Fadin, sov. Phys. JETP **45** (1977) 199; Y. Balitsky and L. Lipatov, Sov. J. Nucl. Phys. **28** (1978) 822; L. Lipatov, Sov. Phys. JETP **63** (1986) 904; S.J. Brodsky, V.S. Fadin, V.T. Kim, L.N. Lipatov and G.B. Pivovarov, SLAC-PUB-8037.

[13] E.M. Levin and M.G. Ryskin, Phys. Rep. **C189** (1990) 267; L.N. Lipatov, Phys. Rep. **C286**, 131 (1997).

[14] J.D. Bjorken, Phys. Rev. **D47** (1993) 101.

[15] V.A. Novikov, M.A. Shifman, A.I. Vainstein and V.I Zakharov, Nucl. Phys **B 165** (1980) 67;**B 191** (1981) 301.

[16] P. Pascual and R. Tarrach, Phys. Lett. **B113** (1982) 495; C.A. Dominguez and N. Paver, Zeit. Phys. **C31** (1986 591; J. Bordes, V. Gimenez and J.A. Penarrocha, Phys. Lett. **B223** (1989) 251.; J. Liu and D. Liu, J. Phys. G: Nucl. Part. Phys. **19** (1993) 373; S. Narison, Nucl. Phys., **B509** (1998) 312.

[17] L.S. Kisslinger, J. Gardner and C. Vanderstraeten, Phys. Lett. **410** (1997) 1.

[18] L..S. Kisslinger and Z. Li, Phys. Lett. **B445** (1999) 271.

[19] D.Z. Freeman and J. Wang, Phys. Rev. **153** (1967) 1596.

[20] BES Collaboration, J.Z. Bai et. al., Phys. Rev. Lett. **76** (1996) 3502.

[21] B.S. Zou abd D.V. Bugg, Phys. **D50** (1995) 591.

[22] Crystal Barrel Collaboration, Phys. Lett. **B355** (1995) 425.

[23] A.H. Mueller, Phys. Reports **73** (1981) 237.

[24] L.C. Liu and W-h. Ma, hep-ph/0001020, J. Phys. **G26** (2000) L59.